rugged mountain systems of the Pacific slope about timber-line.* Very little was known about it up to the eighties, but the West teemed with legends. Its chase lured me to the then equally unknown Kootenay country, and after a most successful hunt lasting six weeks with two Kootenays as my sole companions, the charms of this remote paradise caused me to take more engrossing interest in its development. The ten years I devoted to it were richer than Golconda in experiences, but not in lucre, for mine was the usual fate of those who bite off more than they can chew; and the English company to which I turned over my reclamation concession when I left the country to return to Europe was, for other reasons, equally unsuccessful. I can, however, look back to the financial losses I sustained with a certain degree of satisfaction, for they proved of material assistance to British Columbia. When I began my negotiations with its Government for my concession some wealthy foreign capitalists had nearly secured a land grant of 750,000 acres, including every yard of land round Kootenay Lake and also the overflowed land I wanted. As an eventual consequence of my scheme the foreigners retired altogether, and what very soon afterwards turned out to be one of the richest mineral districts in North America was saved to the province and to individual exploitation by its people.

THE FLUCTUATIONS OF MEAN SEA-LEVEL WITH SPECIAL REFERENCE TO THOSE CAUSED BY VARIATIONS IN BAROMETRIC PRESSURE

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(*The substance, with some revision, of a paper read at one of the meetings for the discussion of Geophysical subjects arranged by a Committee of the British Association, and held in the rooms of the Royal Astronomical Society at Burlington House.*)

IN 1831 M. Daussy, the French Hydrographer, published in the *Additions, Connaissance des Tems* for 1834, a Memoir on the Tides, with special reference to the effect of wind and variation of barometer on mean sea-level at Brest. From a continuous series of observations for 1817 he concluded that a variation of 1 millimetre in the barometer produced a change of opposite sign of 14·7 millimetres in the level of the sea. This appears to be the first determination of the value of the quantity we shall call K, the ratio of change of height of sea to change of barometer. I have recalculated his result from the formula $K = \Sigma w_1 b_1 / \Sigma b_1^2$, where w_1,

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* In my 'Fifteen Years' Sport and Life in the Hunting-grounds of Western America' (the *Field* Office, 1900) I give a synonymy of the Haplocerus, and fully describe its habitat and chase.

w_2, . . . are variations of water-level corresponding with b_1, b_2, . . . variations of barometer, from the mean, and I find $K = -15{\cdot}2$.

In 1837 Mr. J. W. Lubbock published (*Phil. Trans.*, p. 103) an examination of observations at Liverpool and London, and deduced values of K 11·1 and 7·0 (we shall omit the negative sign in the rest of this paper), but it is not clear what observations were used. Mr. Lubbock further "requested Mr. Russell to calculate . . . the height of high water at Liverpool and London for May and June 1836, and compare the calculations with the observations." From the diagrams (*Phil. Trans.*, p. 104) I have calculated that for these months K was 20·1 in Liverpool and 7·7 in London.

Dr. Whewell reported to the British Association (Report, 1841, p. 30) that observations of high water at Bristol in the years 1834–6 gave a ratio 13·3, and that "the effect of atmospheric pressure on the height of the tide is something local and immediate."

In 1842 General Colby asked Sir George Airy to assist him in dealing with a mass of tidal observations round the Irish coast, and the computations were made under Airy's directions at the Royal Observatory. The Astronomer Royal concluded that the comparison amply supported the view that "a negative irregularity in the height of the barometer is accompanied by a positive irregularity in the height of the sea, twelve or fourteen times as great as that of the barometer." I have recomputed the figures for Kingstown and Limerick, and find values of K 8·5 and 16·8.

In 1848 Sir James Ross made hourly observations for nine months, while wintering in the harbour of Port Leopold, lat. 74° N. The complete observations do not seem to have been discussed, but in the *Philosophical Transactions*, 1854, p. 285, will be found the observations of 47 days and values of K ranging from 13·47 to 11·60. I have recomputed the same observations, and find $K = 13{\cdot}5$.

In 1866 Mr. T. G. Bunt published (*Phil. Trans.*, 1867, Part I., p. 5) a comparison of computed and observed heights at high water at Bristol for the twenty-one years 1834 to 1854, and found $K = 12{\cdot}772$.

In the Report of the U.S. Coast Survey for 1871, p. 93, is an examination by Prof. Ferrel of tides in Boston Harbour. From a series of high and low waters from 1856–61 he found $K = 7{\cdot}33$. He remarks that the changes of level appear to anticipate the barometric pressure, and attributes this to certain effects of the wind, which complicate the matter.

In 1895 Mr. W. H. Wheeler contributed to the British Association an examination of the effect of wind and barometer on the tides at Boston Dock, Lincolnshire, and came to negative conclusions, which are probably explained by the distance of Boston Dock from the sea, and its shallow approaches.

In 1896 a Committee of the British Association reported "On the effects of wind and atmospheric pressure on the tides" based on data from Bristol, Hull, Sheerness, Portsmouth, and Liverpool. The Committee found that "the tides are influenced both by atmospheric pressure and wind; that the indications given by the local barometer do not afford a reliable guide; that no reliable formula can be found for the effect of the wind; that the variation of height of water due to atmospheric pressure is thirty times the variation of the mercury." Some exception might perhaps be taken to the methods of calculation adopted, and the stations chosen were perhaps not very suitable, as none of them are open sea stations. The Committee appear to have paid insufficient attention to previous investigations. But the Report deserves study, especially that part of it which deals with the effect of gales.

In 1897 Mr. F. L. Ortt published in *Nature* of May 27 an elaborate examination of tides, wind, and weather for Ymuiden in 1895 and 1896 and the Hook of Holland in 1896, and concluded that the effect of atmospheric pressure on the height of the tides is not the same for different directions of the wind, but qualifies his result with the remark that it is difficult to take into proper account the meteorological effects, which may extend to a great distance. I have re-examined Airy's data for Kingstown, June 22—August 22, 1842, by the method used by Mr. Ortt, and come to much the same conclusion, that the effects of the wind are sensible but somewhat difficult to disentangle. Ortt's mean values of K for all directions of wind are 8·4 at Ymuiden and 12·5 at the Hook of Holland.

In 1914 Prof. D'Arcy Thompson published an important paper on "Mean Sea Level and its Fluctuations" (Fishery Board for Scotland, Scientific Investigations, No. IV., 1914, H.M. Stationery Office. Price 1*s.*). He gives harmonic formulæ for the monthly and annual means of sea-level at Aberdeen, Dundee, Milford Haven, and other ports, but finds it difficult to draw a positive conclusion from the constants. His verdict is, however, that barometric pressure is inadequate to produce the observed variations.

It is no doubt true that the local barometer cannot account fully for the variations, but the Ordnance Survey observations, and the older observations, show clearly that the local barometer has its effect and does account for its expected share. There is an arithmetical error on p. 19 of Prof. Thompson's paper which affects his conclusions. He has shown the existence of a fluctuation with the latitude variation period of 431 days and an amplitude of 1 inch, thus confirming in principle the results of the late General Madsen and Lieut. Petersen.

The above summary of preceding work may serve as an introduction to the following preliminary account of results derived, to a large extent, from the newly established self-recording tide-gauges of the Ordnance Survey.

The Ordnance Survey Observations.—When it was decided to re-execute the geodetic level network of Great Britain, I thought it desirable to take steps to determine with greater accuracy the position of mean sea-level. The late Sir George Darwin was consulted, and he concurred in the selection of mean sea-level stations at Dunbar, Felixstowe, and Newlyn. Felixstowe is, perhaps, not an ideal station, but the other two could hardly be improved; they are open sea stations on a rocky coast. Dunbar has been at work since 1913, Newlyn since 1915, and Felixstowe since 1917. These three points form a great triangle, as nearly equidistant from the centre of England as the shape of England and Wales and the south of Scotland will admit. At each station a self-recording tide-gauge is at work, and there is also a barograph and a mercury barometer. As the Felixstowe station has not been working for quite a year, its records are not included in this discussion.

If for Dunbar and Newlyn we plot, for each year, the monthly variations of mean sea-level, and on the same diagram plot the barometric variations from the mean of the year multiplied by 13¼ (the specific gravity of mercury divided by that of sea-water), and invert the barometer curve, we see at once that there is, in every case, a marked correspondence between the two curves.

But for the present it is not necessary to assume the value of the barometer constant, or K; we can find out what factor does, as a fact, produce the best correspondence. We can do this very simply somewhat as Ferrel did. For each month there is an equation, w_1 (water variation) $= \mathrm{K}b_1$ (barometer variation), and the simple least square solution gives the most probable value of K, viz. $\frac{\Sigma w_1 b_1}{\Sigma {b_1}^2}$. The values obtained in this way for the six years available are :—

	K.
Dunbar, 1913–14	11·5
1914–15	7·3
1915–16	7·3
1916–17	12·1
Newlyn, 1915–16	13·1
1916–17	19·9

It will be seen that K varies a good deal; but it is always negative and appears to be "aiming," so to speak, at the theoretical value.

It will be found that this conclusion is borne out when other stations are examined. The attached tables show the most probable values of K at fifteen different stations. Wherever the observations were available they have been computed in the way above described. Long periods sometimes appear to give results differing more from the theoretical value than short periods. But short periods also show considerable divergencies.

In order to investigate the matter more fully the observations for the year 1916–17 at Newlyn were subjected to special treatment, and it should be remarked that the value of K for this year differed considerably from the mean. The method of treatment was the following: The annual mean sea-level for 1916–17 was first computed as the mean of hourly heights throughout the year. The mean barometer was also computed as the mean of hourly readings throughout the year. Then the mean level for each period of nine tides (each tide being from high to low or low to high) was computed, and the mean barometer reading for this period was also worked out. The 156 barometer variations were then arranged into groups according to magnitude; there were seventeen such groups, and for each group an equation of the form $w = \mathrm{K}b$ was written. The least square solution of these seventeen equations gave as a result, K = 12·4. The calculations were carried out by Major A. C. Robinson, R.E.

It will be noted at once that, whereas by taking monthly means we got a value for K of −19·9, by taking much smaller periods we get a value more approaching the theoretical one. But an inspection of the plotted results gives a more vivid impression than figures do (Plate I.). The immediate response of the sea to the local barometer is very marked. No one after studying this diagram can fail to be convinced that the effect of changes of the barometer on sea-level is a very genuine one. The same result impresses itself on examining Lubbock's diagrams for 1836 at London and Liverpool, or Ross's figures for Port Leopold in 1848, or a tide chart during an atmospheric depression (Plate II.).

Annual Curve.—If the diagrams given by Prof. D'Arcy Thompson for Aberdeen, Dundee, and Milford are plotted on the same paper as those derived from the Ordnance Survey Stations at Dunbar and Newlyn, a general similarity, as might be expected, shows itself; but the Atlantic stations, Milford and Newlyn, are more irregular than the North Sea stations. On the other hand, one cannot expect very regular results from the few years' data available at Milford, Dunbar and Newlyn. An inspection of the diagram (page 56) is sufficient to show that the cause of this annual fluctuation affects the Atlantic as well as the North Sea, and is not to be attributed to any local conditions of the latter.

We can now, applying the proper signs, deduct in each case the appropriate barometer correction, assuming that the local water correction is $-13\frac{1}{4} \times$ local barometer variation. This has been done, and the effect is to depress the curves. If now we take a mean of these "corrected" diagrams we shall obtain the most general result which the observations at present seem to warrant (see Fig. III.). It will be seen that the M.S.L. diagram, corrected for barometer, has a maximum in November and a minimum in April, with a total amplitude of about 6 inches.

M. D. la Cour (quoted by Prof. D'Arcy Thompson), in a paper dealing with M.S.L. in Danish waters, after making allowance for barometric variation, obtained a corrected curve with a maximum about August, a minimum about March, and a total amplitude of about 5 inches. The maximum about August is certainly curious, and does not agree with the British results.

The main conclusions to be derived from the Ordnance Survey observations and the others quoted are, I think, first, that, contrary to the opinions of the British Association Committee and of Prof. D'Arcy

Thompson, variations in the local barometer should be considered as having their full effect on the sea-level, an effect which is, naturally, often masked by fluctuations due to other causes. And the second conclusion is that, superimposed on all other variations, there is an annual tide, probably not astronomical in origin, but oceanic and general, its cause at present unknown; this tide has at the five stations Aberdeen, Dundee, Dunbar, Milford, and Newlyn, a mean amplitude of about 6 inches, with a minimum in March or April.

If the first conclusion is sound it follows that a correction for barometer variations should be applied before discussing the variations due to other causes.

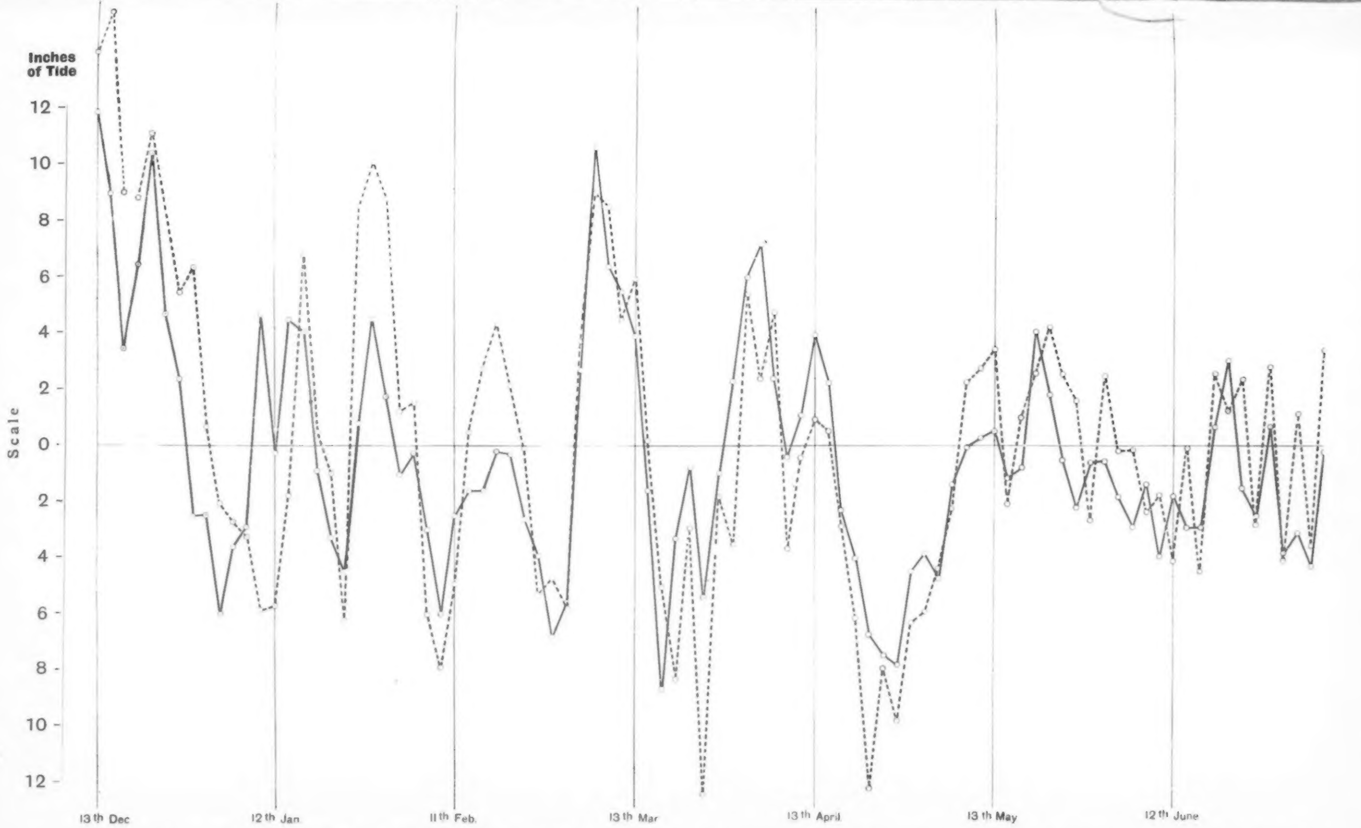
The other variations include a very small nineteen-year tide, a still smaller annual tide, and a small "latitude variation" tide of 431 days' period (Fishery Board for Scotland, Scientific Investigations, 1914, No. 4).

The Ordnance Survey observations have not yet extended over a long enough time to enable us to draw any definite conclusions from them with regard to the variation of mean sea-level *from year to year*. But Dr. Brehmer and Prof. Thompson have shown that there are some general causes at work which give rise to long period fluctuations extending over many years, with a range in our waters of 3 or 4 inches.

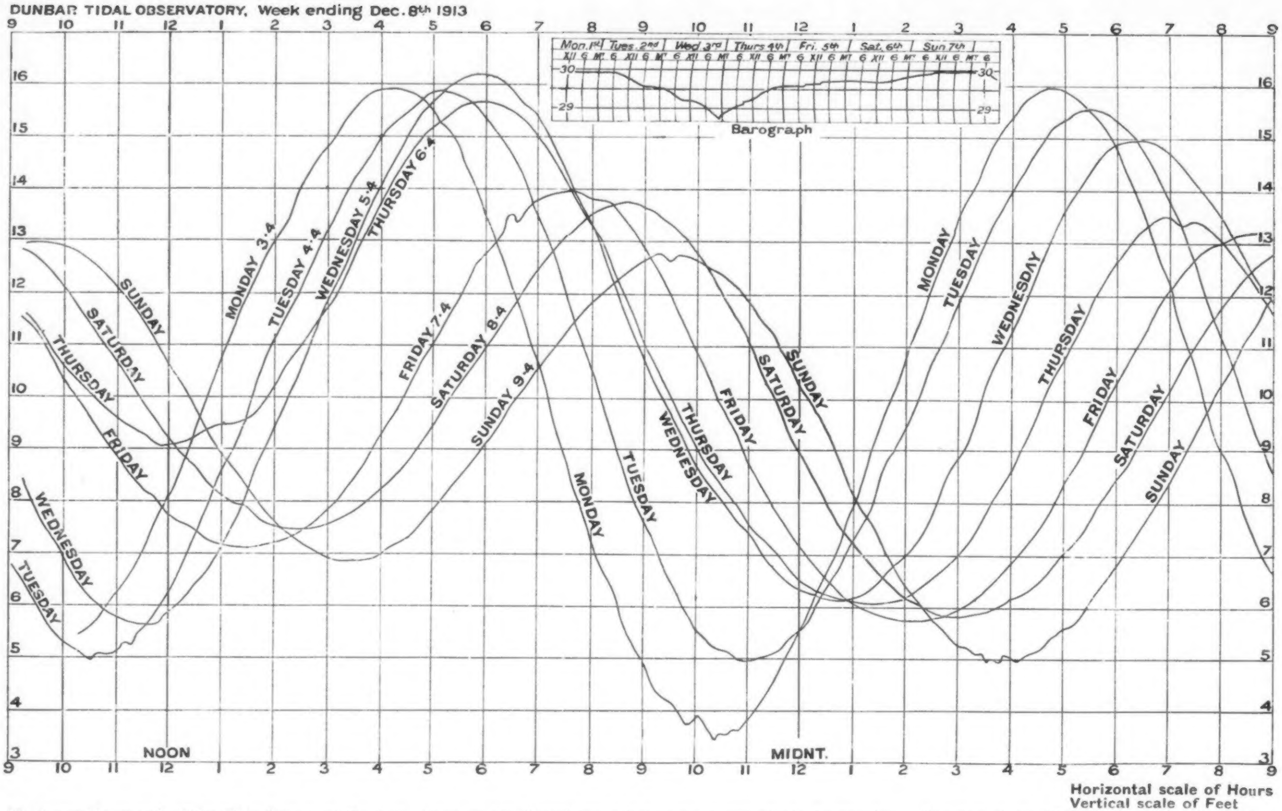
Some Practical Deductions.—On all modern Ordnance maps will be found this legend, "The altitudes are given in feet above the assumed mean level of the sea at Liverpool, which is 0·650 of a foot below the general mean level of the sea." The old mean sea-level at Liverpool was determined in March 1844. If we look at our diagram we shall see that in March the sea-level may be expected to be below the general mean level of the year. We do not know what the value of the annual mean was, and I have not looked up the winds or barometer readings. It is now really an arbitrary datum, no mark remains, and perhaps this point is not worth pursuing. The figure 0·65 foot, or 7·8 inches, is derived from the observations taken at twenty different ports round the coasts of England and Wales in the year 1859, combined with the observations at nine other ports in previous years. At fourteen of the ports the observations were taken during June, July, and August, and July 25 may be taken as a mean date for this group, the rest being scattered throughout the year. The height of the tide was noted at ten-minute intervals, and each day one complete tide was observed, the average number of tides observed being 16½. Altogether nearly 25,000 measurements were made. These were connected with the level network.

If there were any constant error to be expected about July 25 this would affect the mean result. As a fact, our diagrams show that about this time of the year the sea may be expected to be at nearly its mean height, so that, by a happy accident, the result obtained in 1859 is likely to be a fairly good one so far as monthly fluctuations are concerned.

Again, if, as appears to be the case, the "local" barometer exerts its



I. Comparison of Barometer (solid line) and Sea-level (dotted line) at Newlyn, December 1916 to June 1917, showing immediate response of Sea to local Barometer. The Sea-levels are the means of hourly readings over nine tides (high to low or low to high); the Barometer values are means of hourly readings over the same periods, inverted and multiplied by 13.25. Horizontal line is mean level for the year.



II. A week's record of the Tide Gauge at Dunbar, showing the disturbing effect of an Atmospheric Depression. The age of the Moon at noon is given after the second set of names of days of week

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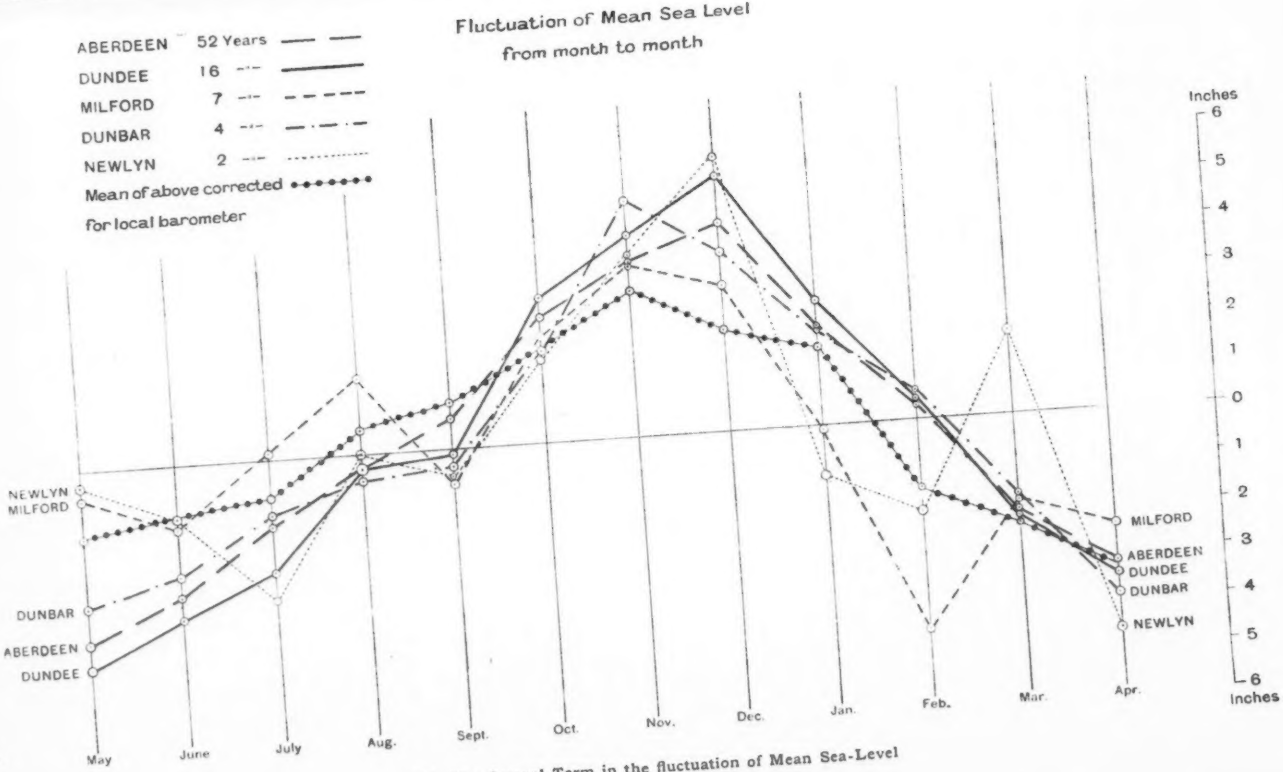

III. The Annual Term in the fluctuation of Mean Sea-Level full effect in raising or depressing the mean level of the sea, then our three mean sea-level stations, Dunbar, Newlyn, and Felixstowe, will have their mean level, over a long period, affected by the permanent difference of height of barometer. The Meteorological Office has kindly given me the Normal Pressure Values for these three stations, and it appears that the normal barometer at Newlyn is somewhat more than one-tenth of an inch of mercury higher than it is at Dunbar. From this cause, therefore, the mean sea-level at Newlyn would be 1·4 inches below the mean sea-level at Dunbar. The difference would not be detected by any levelling operation, and apparently should be allowed for in the general reduction of the levelling—if based on the three values of M.S.L.

Values of K (Ratio of variation of M.S.L. to variation of local barometer) for periods of one year and longer.

Place.	Dates.	Number of years.	Authority.	K	Remarks.
Brest	1817	1	Daussy	15·2	*Recomputed
Liverpool	?	?	Lubbock	11·1	*Phil. Trans.*, 1837
London	?	?	,,	7·0	,, ,, 1837
Bristol	1834–54	21	Bunt	12·8	Mean of yearly values
Boston (U.S.A.) ...	1856–61	6	Ferrel	7·3	From computed mean tides
Aberdeen	1862–1913	52	Harb. Eng.	32·8	*Bar. from Met. Office
Dundee	1867–1912	46	,, ,,	21·3	* ,, ,, ,,
Milford	1886–92	7	Admiralty	17·6	* ,, ,, ,,
Ymuiden	1895–96	2	Ortt	8·4	Mean of all winds
Hook of Holland	1896	1	,,	12·5	,, ,, ,,
Dunbar	1913–17	4	O. S.	9·6	*Mean of yearly values
Newlyn	1915–17	2	,,	16·5	* ,, ,, ,,
[Newlyn	1916–17	1	,,	12·2]	*Computed for every nine tides: Robinson

Values of K for periods of less than one year.

Place.	Dates.	Number of days.	Authority.	K	Remarks.
Liverpool	1836	61	Lubbock	20·1	Recomputed
London	1836	61	,,	7·7	,,
Kingstown ...	1842	61	Airy	8·5	,,
Limerick	1842	61	,,	16·8	,,
Port Leopold ...	1848	47	Ross	13·5	* ,,

The results marked * in the above lists depend upon a comparison of observed M.S.L. of short periods with observed M.S.L. of long periods. The results not so marked depend generally on a comparison of observed with computed values, and are not so reliable.'